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NASA TN D-1773

N63-15526
code 1

NASA TN D-1773

TECHNICAL NOTE

D-1773

SIMULATOR STUDY OF THE LATERAL-DIRECTIONAL HANDLING QUALITIES OF A LARGE FOUR-PROPELLERED STOL TRANSPORT AIRPLANE

By Hervey C. Quigley and Herbert F. Lawson, Jr.

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NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

WASHINGTON May 1963

36p 554418

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SUMMARY

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The lateral and directional stability and control characteristics of a large four-propellered STOL transport airplane (the boundary-layer-control equipped NC-130B) have been studied on the landing approach simulator to determine changes in the characteristics that might be required to achieve satisfactory lateral-directional handling qualities. The study has shown that the handling qualities can be improved by increased directional stability and damping. A large increase in stability in conjunction with increased yaw rate damping gave some improvement, but the reduced directional response to rudder inputs prevented the configuration from being rated satisfactory by the evaluating pilots. A satisfactory configuration was achieved by doubling the basic directional stability and including a damping term which gave yawing moments proportional to rate change of sideslip.

INTRODUCTION

With interest in STOL aircraft increasing, there is a need to establish handling qualities requirements for this type of vehicle. Reference 1 indicates that many STOL handling qualities items require additional study to define satisfactory characteristics. The flight investigations of references 2 and 3 pointed out that one of the major problem areas for large STOL vehicles was the lateral-directional mode. In both of these investigations, controlling sideslip was the primary control problem for the pilot when maneuvering during low-speed landing approaches. In addition, the pilot commented on poor control response, adverse yaw, low directional stability, and poor directional damping. Because of the difficulty of investigating a wide range of lateral-directional parameters in flight, the airplane of reference 2 (BLC equipped NC-130B) was programmed on the Ames landing approach simulator. The lateral-directional stability and control characteristics were evaluated on the simulator by three NASA research pilots, with experience in the airplane, to determine which parameters should be improved to achieve satisfactory handling qualities. The study was limited to defining values of these parameters necessary to improve the specific airplane being simulated, and no attempt was made to map complete boundaries between satisfactory and unsatisfactory characteristics.

NOTATION

b	wing span
C_l	rolling-moment coefficient, $\frac{L}{qSb}$
C_n	yawing-moment coefficient, $\frac{N}{qSb}$
C_Y	side-force coefficient, $\frac{Y}{qS}$
C_{l_p}	$\frac{\partial C_l}{\partial(pb/2V)}$, per radian
C_{l_r}	$\frac{\partial C_l}{\partial(rb/2V)}$, per radian
C_{l_β}	$\frac{\partial C_l}{\partial \beta}$, per radian
$C_{l_{\delta_a}}$	$\frac{\partial C_l}{\partial \delta_a}$, per radian
$C_{l_{\delta_r}}$	$\frac{\partial C_l}{\partial \delta_r}$, per radian
C_{n_p}	$\frac{\partial C_n}{\partial(pb/2V)}$, per radian
C_{n_r}	$\frac{\partial C_n}{\partial(rb/2V)}$, per radian
C_{n_β}	$\frac{\partial C_n}{\partial \beta}$, per radian
$C_{n_{\dot\beta}}$	$\frac{\partial C_n}{\partial(\dot\beta b/2V)}$, per radian

$C_{n_{\delta_a}}$	$\frac{\partial C_n}{\partial \delta_a}$, per radian
$C_{n_{\delta_r}}$	$\frac{\partial C_n}{\partial \delta_r}$, per radian
C_{Y_β}	$\frac{\partial C_Y}{\partial \beta}$, per radian
$C_{Y_{\delta_r}}$	$\frac{\partial C_Y}{\partial \delta_r}$, per radian
L	rolling moment, ft-lb
M	pitching moment, ft-lb
N	yawing moment, ft-lb
DR	damping ratio, $\frac{0.693}{T_{1/2}\omega_n}$
p	rate of roll, radians/sec
q	free-stream dynamic pressure, lb/ft^2
r	rate of yaw, radians/sec
S	wing area, ft^2
V	velocity, ft/sec
Y	side force, lb
$T_{1/2}$	time to damp to one-half amplitude
α	angle of attack, deg
β	sideslip angle, radians or degrees
$\dot{\beta}$	rate change at sideslip, radians/sec
δ_a	aileron position, radians or degrees
δ_r	rudder position, radians or degrees

φ angle of bank, radians or degrees

ψ yaw angle, deg

ω_n undamped natural frequency, radians/sec

EQUIPMENT AND TEST

Simulator

The fixed transport-type cockpit used in this investigation was equipped with a conventional instrument display and normal flight controls. A Dalto Visual Simulator, a closed-circuit television system with the camera servo-driven over a model runway, projected the approach lighting and runway as they would be seen in hazy, one-half mile visibility. Figure 1 is a photograph of the projected display taken from the pilot's position inside the cockpit. A pictorial block diagram of the simulation is shown in figure 2. Six-degrees-of-freedom equations of motion were programmed on the analog computer.

The NC-130B airplane was simulated in the landing configuration. A photograph of the airplane is shown in figure 3. This airplane was equipped with blowing-type boundary-layer control on the plain trailing-edge flaps, drooped ailerons, elevator, and rudder. In the present studies the trailing-edge flaps were assumed to be deflected 70°, the aileron drooped 30°, and the landing gear extended. The inertia characteristics corresponded to a normal fuel distribution for a gross weight of 100,000 pounds. The stability and control derivatives and lift-drag characteristics used in the simulation were determined from the results of the flight investigation (ref. 3). The various derivatives were estimated from the flight test data and then adjustments were made on the computer until time histories of the response to step control inputs on the simulator agreed with those in flight. As shown in figure 4 the responses of the airplane to an aileron pulse input as measured in flight and from the simulation are almost identical. Table I tabulates the lateral-directional stability and control derivatives used to define the basic configuration and the range of values used in the simulation program. Figure 5 indicates the direction for positive forces and moments. The lift-drag characteristics were programmed to be representative only at an engine power required for a 3° approach angle. However, the changes in lift and drag with power changes at airspeeds near 70 knots or airspeed changes with approach power were simulated quite realistically. This simplification did not compromise the simulation, since the task the pilot "flew" on the simulator was to maintain about 70 knots and a 3° approach angle.

Test and Procedure

The three NASA research pilots who flew the NC-130B airplane in the flight evaluation also participated in the simulator tests. After a short adaptation period, the pilots felt that the simulation was realistic and were able to rate changes. The pilots rated the characteristics by the Cooper pilot rating system (ref. 4). Table II summarizes the rating system.

The pilots began their simulated approach at 200 feet altitude and 5,000 feet from the end of the runway, with the approach lights barely visible. The pilots "flew" from this initial point to the runway maintaining between 65 and 70 knots airspeed while evaluating the following:

1. Damping as indicated by response to rudder pulses
2. Sideslip by banking to 10° with rudder fixed
3. Positioning of the airplane by maneuvering from one side of runway to the other
4. Time and distance required to reduce sideslip to zero from a stabilized steady-state sideslip of 10°
5. Normal landing approach to touchdown with a 10-knot crosswind

The pilots' procedure for rating the various configurations was, first, to evaluate the basic airplane configuration, then change a derivative or group of derivatives that would affect the lateral-directional handling qualities and evaluate the new configuration. The configuration would be returned to the basic before another derivative was changed. In this way, the pilots always related their evaluations to the basic configuration. This procedure did not establish boundaries, but did determine what the pilots considered to be near optimum for this airplane. The derivatives were changed over a range that was considered to be somewhat realistic for an airplane of the C-130 size and weight with a stability augmentation system or with modification effecting the aerodynamics, such as an enlarged tail. The study was concerned only with the lateral-directional characteristics; therefore, the longitudinal characteristics were not evaluated.

RESULTS AND DISCUSSION

Statement of Problem

Flight evaluation of the NC-130B STOL airplane (ref. 3) pointed out that large sideslip excursions accompanied landing approach maneuvers and the heading could not be controlled precisely, particularly in ILS approaches, without continuous reference to a sideslip indicator in the cockpit. The problem is illustrated in a time history of the response of the basic airplane to a rudder-fixed banked turn shown in figure 4. As the airplane was banked to the left about 12°, the initial yaw rate was to the right, opposite to the turn, because of the adverse yaw produced by aileron deflection. As the ailerons were neutralized, the airplane turned in the direction of the bank. At the same time, sideslip developed rapidly to over 8°. The sideslip which resulted from the lateral acceleration when the lift vector was tilted built up until a turn rate was established. Since the directional stability of the airplane was very low, as indicated by the long period (12 seconds per cycle) of the directional oscillation, large sideslip angles and an appreciable time period were required to establish the desired turn rate. In addition, the directional oscillatory characteristics were poorly damped (damping ratio of 0.1). In the actual airplane the problem was also complicated by very undesirable mechanical characteristics of the control system, especially the rudder control, which made it difficult for the pilot to augment the basic stability and damping.

Effect of Improved Control

Since the over-all control characteristics of the airplane about all three axes had been rated unsatisfactory in flight (ref. 3), it was anticipated that improved lateral and directional control would give the pilot a better means of controlling sideslip. The control parameters considered were the mechanical characteristic of the flight control system, lateral and directional control powers, lateral damping, and lateral-directional control cross coupling. Table III summarizes the results of this phase of the tests. It should be pointed out that the pilots rated the over-all dynamic lateral-directional characteristics of the airplane and not the individual parameter that was varied.

Control system mechanical characteristics.- The mechanical characteristics of the airplane control system were very undesirable, as pointed out in reference 3. However, as a base for pilots' rating, it was necessary to approximate the airplane control system on the simulator. It was not possible to duplicate the feel characteristics, but by the use of springs and friction brakes a reasonable simulation was obtained. Table IV(a) lists the values of the spring gradient and friction used. With the high values of control friction, the pilots rated the lateral-directional characteristics of the airplane as unacceptable and dangerous, a numerical rating of 8. The pilots' rating of the airplane in flight was 6-1/2. The difference indicates that good control-system feel is even more critical in simulators than in flight. The absence of control centering was of major concern to the pilots in the simulator because of the lack of motion and peripheral vision cues. It was found that when the excessive friction and high spring gradients were removed from the controls, the pilots' ratings on the simulator were raised to the flight rating of 6-1/2. The final spring gradients used and the inherent friction of the simulator are noted in table IV(b). These values were not necessarily optimum for STOL operation but were found to be acceptable and were used for the remainder of the tests.

Lateral control characteristics.- The results of varying the lateral control power and damping are presented in table III. Increasing the lateral control power, $C_{l_{\delta_a}}$, by a factor of 2 changed the pilots' rating from 6-1/2 to 5-1/2. Increasing $C_{l_{\delta_a}}$ above this value would have made lateral control too sensitive. Increasing roll damping (C_{l_p}) alone made it somewhat easier for the pilots to control bank angle and resulted in a pilot rating of 5; increasing both control power and damping did not result in a better rating. Although the pilots liked the improved control power and damping, it did not improve control of sideslip.

It should be pointed out that the task used in the simulation did not afford the pilot an over-all evaluation of control power and damping since only limited maneuvering was possible in the final approach and no motion cues were present.

Directional control characteristics.- Increasing the directional control power gave no significant improvement. Table III shows that doubling the directional control power changed the pilots' rating from 6-1/2 to 6. Again, the pilots liked the increased control, but they considered even the basic directional control sensitivity too high (0.06 inch of pedal per degree sideslip) for precise sideslip control. With an airplane with low directional stability the problem of how to define the directional control requirements arises. Adequate directional control power for maneuvering requires very high sensitivity in terms of the rudder required per degree of sideslip. More research is required to determine the relative importance of manuevering and of precise directional control requirements.

Effect of control cross coupling.- The main source of control cross coupling came from adverse yaw due to aileron deflection $C_{n_{\delta_a}}$. Its elimination did not change the pilot rating nor did the elimination of both adverse yaw and yawing moment due to roll rate, C_{n_p}. The fact that the elimination of adverse yaw did not help the pilot was somewhat surprising. The pilots felt that the amount of adverse yaw was not excessive and could be controlled with a good control system. Since one of the characteristics of the problem was the time required to establish a turn rate after a bank angle was initiated, a yawing moment proportional to aileron deflection, aileron-rudder interconnect, was tried to provide a yawing moment in the direction of the turn. Some improvement was indicated by this configuration (pilot rating of 5). The particular aileron-rudder interconnect used was deficient in that yawing moment was a function of the aileron deflection and as soon as the ailerons were neutralized the augmentation disappeared.

Effect of Improved Stability and Damping

It was concluded that changes in lateral or directional control characteristics alone would not solve the problem. Therefore, the next approach was to study the effect of improved directional stability and/or damping. Table V summarizes the results obtained in this phase of the investigation.

Effect of directional stability.- In the study of the effect of the directional stability derivative C_{n_β}, it was recognized that as C_{n_β} was increased, both the directional response and the maximum attainable sideslip angle with full rudder would be reduced. Therefore, it was desirable that a satisfactory configuration be achieved with as little increase in directional stability as possible. The limit on the increase in C_{n_β} was arbitrarily set at four times basic which gave a maximum sideslip of $\pm 15^\circ$ β with full rudder deflection. When C_{n_β} was first increased without changing the damping, little improvement was possible, as noted in table V. As the stability was increased, the damping ratio was reduced even further and it appeared to the pilot that the damping had actually decreased.

Effect of directional damping.- The next approach was to vary the yaw rate damping, C_{n_r}, as C_{n_β} was changed. The gains are illustrated in figure 6. Increasing the yaw rate damping alone caused only a small gain with a damping ratio of 0.6 (C_{n_r} increased 4 times) giving the best rating of 6, but the improvement was significant when both directional stability and yaw rate damping were increased. A pilot's rating of 4 (almost satisfactory) was achieved by a C_{n_β} value of 0.800 (four times the basic airplane) and at a damping ratio of 0.45 (C_{n_r} increased six times). Further gains were not possible by varying stability and damping because of the airplane's poor response. At the high values of C_{n_β} and high damping the aircraft was too sluggish for maneuvering. Even with the best of these configurations, the control of sideslip was still a problem.

Effect of increasing dihedral (C_{l_β}).- In an attempt to alert the pilot to the build-up in sideslip, C_{l_β} was increased six times basic in the configuration consisting of C_{n_β} increased four times and C_{n_r} increased six times. The increase in C_{l_β} did not change the pilot rating of 4. The pilots commented that too large a sideslip angle was required to give a recognizable roll response and therefore control of the sideslip excursions did not improve. The high moment of inertia in roll was a contributing factor to the low roll response.

Effect of sideslip rate damping.- Since the problem was to control sideslip development, the next step investigated sideslip rate damping $C_{n_{\dot\beta}}$ (referred to as $\dot\beta$ damping in the remainder of the report). The initial evaluation of various amounts of $\dot\beta$ damping with the basic value of C_{n_β} showed that with a $C_{n_{\dot\beta}}$ of 1.9 (damping ratio of 2), the control of sideslip was significantly improved. Because of the sluggish response to intentional sideslipping, however, the pilots rated this configuration only 4. The sluggish response was evident when rapid changes in sideslip were required as, for example, when touching down in a crosswind. Increasing directional stability C_{n_β} by 2 permitted the damping ratio to be reduced to 0.7 ($C_{n_{\dot\beta}} = 1$) with a pilot's rating of 3-1/2, placing this configuration in the satisfactory region as shown in figure 6. Increasing C_{n_β} to four times the basic airplane value required no change in the value of $C_{n_{\dot\beta}}$ although the damping ratio would be reduced to 0.5. This configuration resulted in the best configuration achieved during the simulation (pilot rating of 3); however, increasing C_{n_β} from two to four times resulted in a change of only one-half of a pilot rating. Therefore, the advisability of the higher stability would be questionable.

An analysis was made to determine why $\dot\beta$ damping was more effective than yaw rate damping. Calculations were made to show the sideslip β and yaw rate r response following a step bank angle input for three cases: (1) no rate damping, (2) yaw rate damping alone, and (3) $\dot\beta$ damping alone. The simplified equations and the method used for solving them are included in the appendix and the results of the calculations are presented in figure 7 in time history form.

These data show that with no damping, except that provided by C_{Y_β}, both sideslip and yaw rate are oscillatory with a period of 12 seconds. When yaw rate damping is included it can be seen that the yaw rate builds up very slowly. In fact, it takes about 5 seconds for a steady turn to build up and a β of about 6° is required for trimmed flight in the turn. In the $\dot{\beta}$ damping case, a steady-state turn rate is built up in about 2-1/2 seconds with a peak sideslip angle of less than 2°, and turn rate decreases slightly as sideslip decreases. The response of the airplane to yaw and $\dot{\beta}$ damping differs as a result of the direction of the initial moment as the airplane is banked. In the $\dot{\beta}$ case, as the airplane moves laterally, due to bank angle, the yawing moment, due to $\dot{\beta}$ damping, is in the direction of the turn while yaw damping is always opposite to the turn. This shows that initially $C_{n_{\dot{\beta}}}$ is acting more as a stability term than a damping term with respect to the directional response. As a further comparison, figure 8 presents the response of the airplane as obtained from the simulator to the same aileron input used in the early portion of the report to describe the problem. This figure shows graphically the change when the basic airplane is modified to provide either yaw rate or $\dot{\beta}$ damping. It can be seen that the responses are similar for both configurations, but with more sideslip evident in the yaw damping case. Although C_{n_β} with the yaw damping is twice that with the $\dot{\beta}$ damping, the time to peak turn rate is about the same for both.

Implementing Improved Stability and Damping

A brief study was made to determine methods of implementing the improved directional stability and damping. Calculations have shown that to increase C_{n_β} from 0.200 to 0.800 on the NC-130B airplane by aerodynamic means would require increasing the vertical-tail area by approximately 130 percent if the aerodynamic center of the vertical tail remained the same. It would take an even larger vertical tail to make a significant improvement in damping. A practical way to implement increased damping and stability is with a stability augmentation system (SAS). The gains required in an SAS to achieve various C_{n_β}, $C_{n_{\dot{\beta}}}$, and C_{n_r} are shown in figure 9. The gains are in terms of the ratio of the change in rudder deflection with change in β, $\dot{\beta}$, and r. These data show that fairly high gains are required for the configurations that gave satisfactory handling qualities (see table V). The movement of the servo rudder required to augment the stability and damping in the bank-turn maneuver is included in figure 8. The maximum rudder authority required for the SAS during the limited maneuvering with a satisfactory configuration on the simulator was about 25 percent of maximum rudder deflection. However, these maneuvers were limited to about 10° bank turns and 10-knot crosswind. If the airplane were to be operated in a confined area, steeper bank turns would be required. In this type of maneuvering the SAS may require as high as 80 percent maximum rudder deflection. A flight investigation is required to determine whether so much rudder deflection is necessary or the rudder authority of the SAS could perhaps be limited to 25 percent and still achieve satisfactory handling qualities. It appears from the analysis that an SAS could be incorporated into the NC-130B to check the results obtained in the simulation.

CONCLUDING REMARKS

A simulator study of the lateral-directional characteristics of a large STOL transport airplane (NC-130B) has shown that the problem of controlling sideslip at the low airspeeds required for STOL operation, is due for the most part to low directional stability and damping. Simply increasing the control power or including a yaw rate damper did not improve the lateral-directional handling qualities significantly. Some improvement was possible when both directional stability and yaw rate damping were increased but the reduced directional response of this configuration prevented it from being completely satisfactory. A satisfactory configuration was achieved by doubling the directional stability and including a term that gave a yawing moment proportional to rate change of sideslip. The level of damping provided by the rate change of sideslip term gave a damping ratio of 0.7. This value was a compromise with a large amount that was desirable for maneuvering flight, but was found to be satisfactory on the simulator. A flight study is required to check these results and to determine the optimum gains to give satisfactory lateral-directional handling qualities.

Ames Research Center
National Aeronautics and Space Administration
Moffett Field, Calif., Feb. 19, 1963

APPENDIX

EQUATIONS AND ASSUMPTIONS USED IN RESPONSE CALCULATIONS

The following simplified equations were used to compute the sideslip and turn-rate response of the airplane to a step bank angle input. (The results of these calculations are presented in fig. 7.)

SIDESLIP

$$\left[\text{Mass} \times \begin{matrix}\text{Lateral}\\ \text{acceleration}\end{matrix}\right] = \left[\begin{matrix}\text{Side force}\\ \text{due to bank angle}\end{matrix}\right] - \left[\begin{matrix}\text{Centrifugal force}\\ \text{due to turn rate}\end{matrix}\right] - \left[\begin{matrix}\text{Aerodynamic}\\ \text{side force}\end{matrix}\right]$$

$$A_Y\left(\frac{W}{g}\right) = W \sin \varphi - \frac{W}{g} rV + Y_\beta \beta$$

$$v_y = \int_0^t A_Y \, dt = \int_0^t \left(g \sin \varphi - rV + Y_\beta \beta \frac{g}{W}\right) dt$$

$$\beta = \sin^{-1} \frac{v_y}{V}$$

where

A_Y lateral acceleration, ft/sec^2

v_y lateral velocity, ft/sec

V forward velocity, ft/sec

t time

YAW RATE

$$r = \int_0^t \left(\frac{N_\beta \beta}{I} + \frac{N_r r}{I}\right) dt$$

or

$$r = \int_0^t \left(\frac{N_\beta \beta}{I} + \frac{N_{\dot\beta} \dot\beta}{I}\right) dt$$

where

N_β yawing moment due to sideslip, $\frac{\partial N}{\partial \beta}$, $\frac{\text{ft-lb}}{\text{radian}}$

N_r yawing moment due to yaw rate, $\frac{\partial N}{\partial r}$, $\frac{\text{ft-lb}}{\text{radians/sec}}$

$N_{\dot\beta}$ yawing moment due to rate change of sideslip, $\frac{\partial N}{\partial \dot\beta}$, $\frac{\text{ft-lb}}{\text{radians/sec}}$

An approximate solution to these equations was obtained using the numerical method shown below:

$$v_{y(n)} = v_{y(n-1)} + \left[g \sin \varphi - r_{(n-1)} V + Y_\beta \beta_{(n-1)} \frac{g}{W}\right] \Delta t$$

$$\beta_{(n)} = \sin^{-1} \frac{v_{y(n)}}{V}$$

$$r_{(n)} = r_{(n-1)} + \left[\frac{N_\beta}{I} \beta_{(n)} + \frac{N_r}{I} r_{(n-1)}\right] \Delta t$$

or

$$r_{(n)} = r_{(n-1)} + \left[\frac{N_\beta}{I} \beta_{(n)} + \frac{N_{\dot\beta}}{I} \frac{\beta_n - \beta_{(n-1)}}{\Delta t}\right] \Delta t$$

where

$\Delta t = 0.1$ sec from $t = 0$ to $t = 5$ sec

$\Delta t = 0.5$ sec from $t = 5$ to $t = 10$ sec

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3. Quigley, Hervey C., and Innis, Robert C.: Handling Qualities and Operational Problems of a Large Four-Propeller STOL Transport Airplane. NASA TN D-1647, 1963.

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TABLE I.- LATERAL-DIRECTIONAL DERIVATIVES

Derivative	Basic airplane value	Range of values used in simulation
C_{l_p}	-1.02	-1.02 to -1.53
C_{l_r}	.096	not varied
C_{l_β}	-.067	-0.067 to -0.402
$C_{l_{\delta_a}}$	.200	0.200 to 0.400
$C_{l_{\delta_r}}$	-.022	not varied
C_{n_p}	.028	0 to 0.028
C_{n_r}	-.231	-0.231 to -1.386
C_{n_β}	.200	0.200 to 0.800
$C_{n_{\dot{\beta}}}$	0	0 to 2.50
$C_{n_{\delta_a}}$	-.045	-0.045 to +0.07
$C_{n_{\delta_r}}$	.220	-0.110 to -0.440
C_{Y_β}	-.718	not varied
$C_{Y_{\delta_r}}$	.674	not varied

TABLE II.- PILOT OPINION RATING SYSTEM FOR UNIVERSAL USE

	Adjective rating	Numerical rating	Description	Primary mission accomplished	Can be landed
Normal operation	Satisfactory	1	Excellent, includes optimum	Yes	Yes
		2	Good, pleasant to fly	Yes	Yes
		3	Satisfactory, but with some mildly unpleasant characteristics	Yes	Yes
Emergency operation	Unsatisfactory	4	Acceptable, but with unpleasant characteristics	Yes	Yes
		5	Unacceptable for normal operation	Doubtful	Yes
		6	Acceptable for emergency condition only[1]	Doubtful	Yes
No operation	Unacceptable	7	Unacceptable even for emergency condition[1]	No	Doubtful
		8	Unacceptable - dangerous	No	No
		9	Unacceptable - uncontrollable	No	No

[1]Failure of a stability augmenter

TABLE III.- SUMMARY OF THE EFFECT OF CONTROL

	Pilot Rating
Basic airplane (high friction)	8
Basic airplane (low friction)	6-1/2
$C_{l_{\delta_a}}$ increased from 0.200 to 0.400	5-1/2
C_{l_p} increased from -1.02 to -1.53	5
$C_{l_{\delta_a}}$ increased from 0.200 to 0.400; C_{l_p} increased from -1.02 to -1.53	5-1/2
$C_{n_{\delta_r}}$ increased from 0.220 to 0.440	6
$C_{n_{\delta_a}}$ reduced to 0	6-1/2
$C_{n_{\delta_a}}$ & C_{n_p} reduced to 0	6-1/2
Aileron - rudder interconnect ($C_{n_{\delta_a}}$ = 0.07)	5

TABLE IV.- MECHANICAL CHARACTERISTICS OF CONTROL SYSTEM

Control	Deflection	Friction	Spring gradient
(a) Values used to simulate undesirable control feel characteristics of airplane			
Lateral	±90°	8 lb	0.20 lb/deg
Directional	±3.75 in.	20 lb	30 lb/in.
Longitudinal	9-1/2 in. aft, 7 in. fwd	6 lb	7.5 lb/in.
(b) Acceptable values of friction and spring gradient			
Lateral	±90°	1.3 lb	0.20 lb/deg
Directional	±3.75 in.	7 lb	16.0 lb/in.
Longitudinal	9-1/2 in. aft, 7 in. fwd	1 lb	7.5 lb/in.

TABLE V.- SUMMARY OF THE EFFECT OF STABILITY AND DAMPING

	Pilot Rating
Basic airplane	6-1/2
C_{n_r} increased from -0.231 to -1.386	5-1/2
C_{n_β} increased from 0.200 to 0.800	5-1/2
C_{n_β} increased from 0.200 to 0.800 C_{n_r} increased from -0.231 to -1.386	4
C_{n_β} increased from 0.200 to 0.800 C_{n_r} increased from -0.231 to -1.386 . . . . C_{l_β} increased from -0.067 to -0.402	4
$C_{n_{\dot\beta}}$ added ($C_{n_{\dot\beta}}$ = 1.9)	4
C_{n_β} increased from 0.200 to 0.400 $C_{n_{\dot\beta}}$ added ($C_{n_{\dot\beta}}$ = 1)	3-1/2
C_{n_β} increased from 0.200 to 0.800 $C_{n_{\dot\beta}}$ added ($C_{n_{\dot\beta}}$ = 1)	3

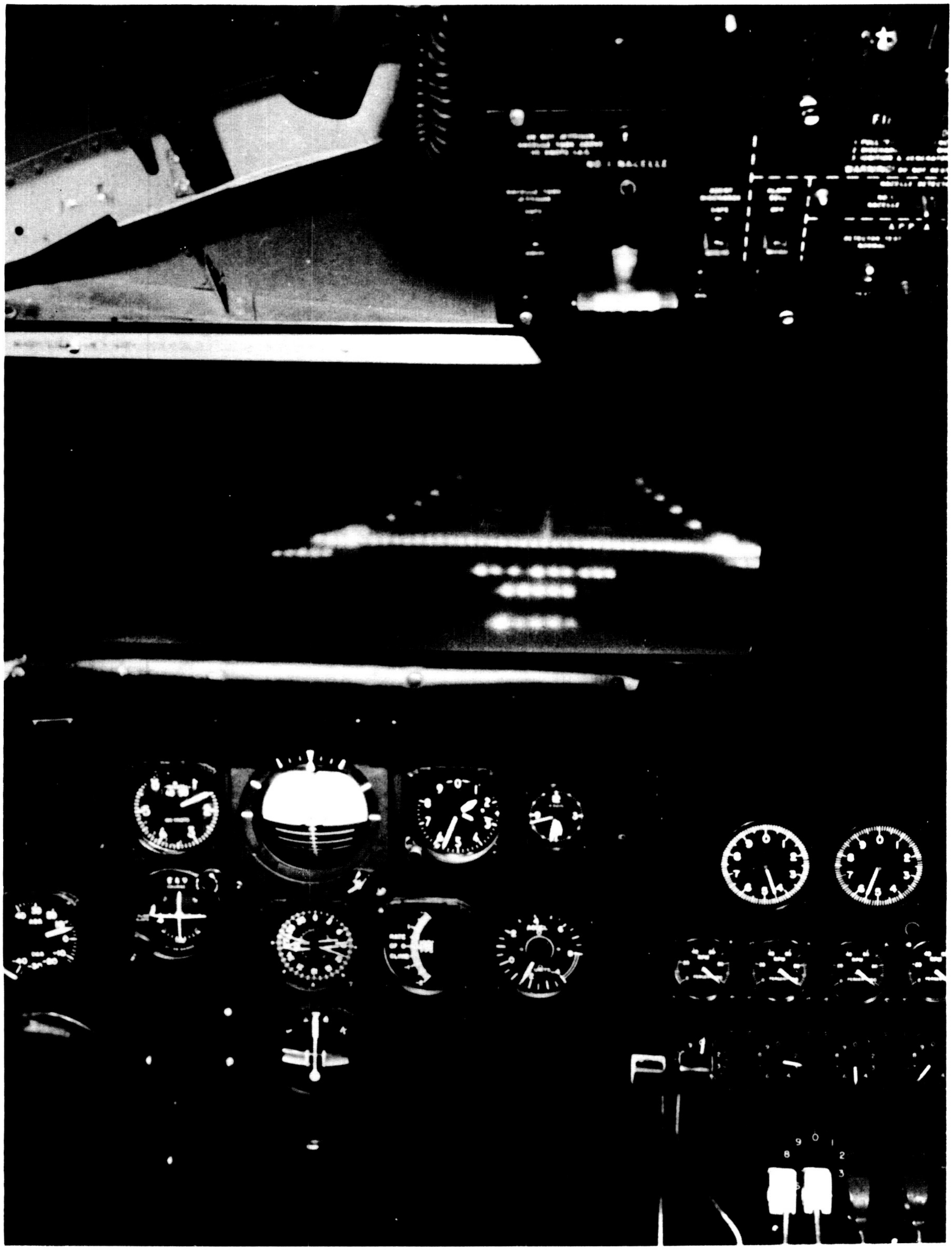

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Figure 1.- Photograph of instrument display and projected runway from pilot's position inside simulator cab.

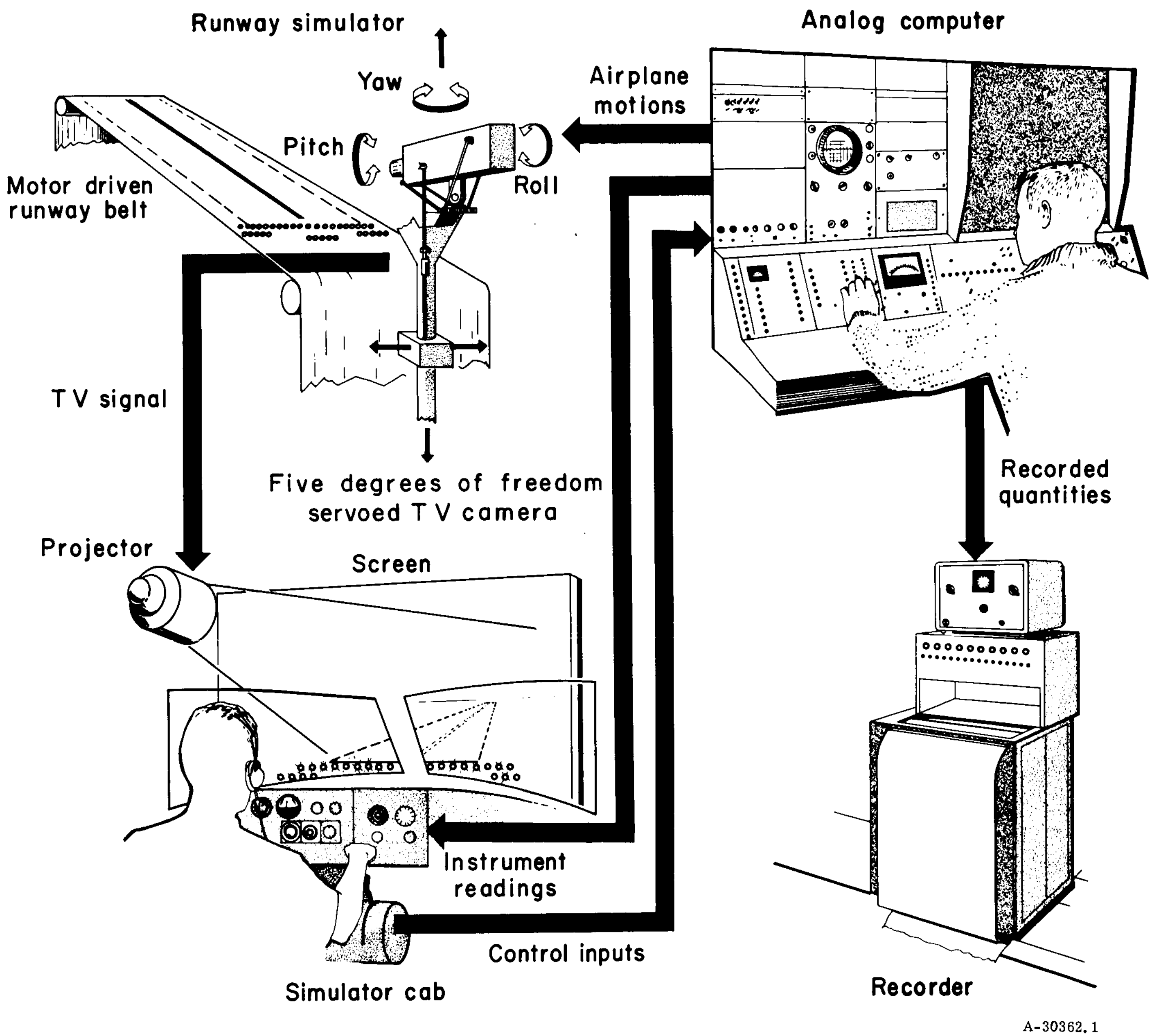

Figure 2.- Pictorial block diagram of the landing approach simulator.

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Figure 3.- Photograph of NC-130B airplane.

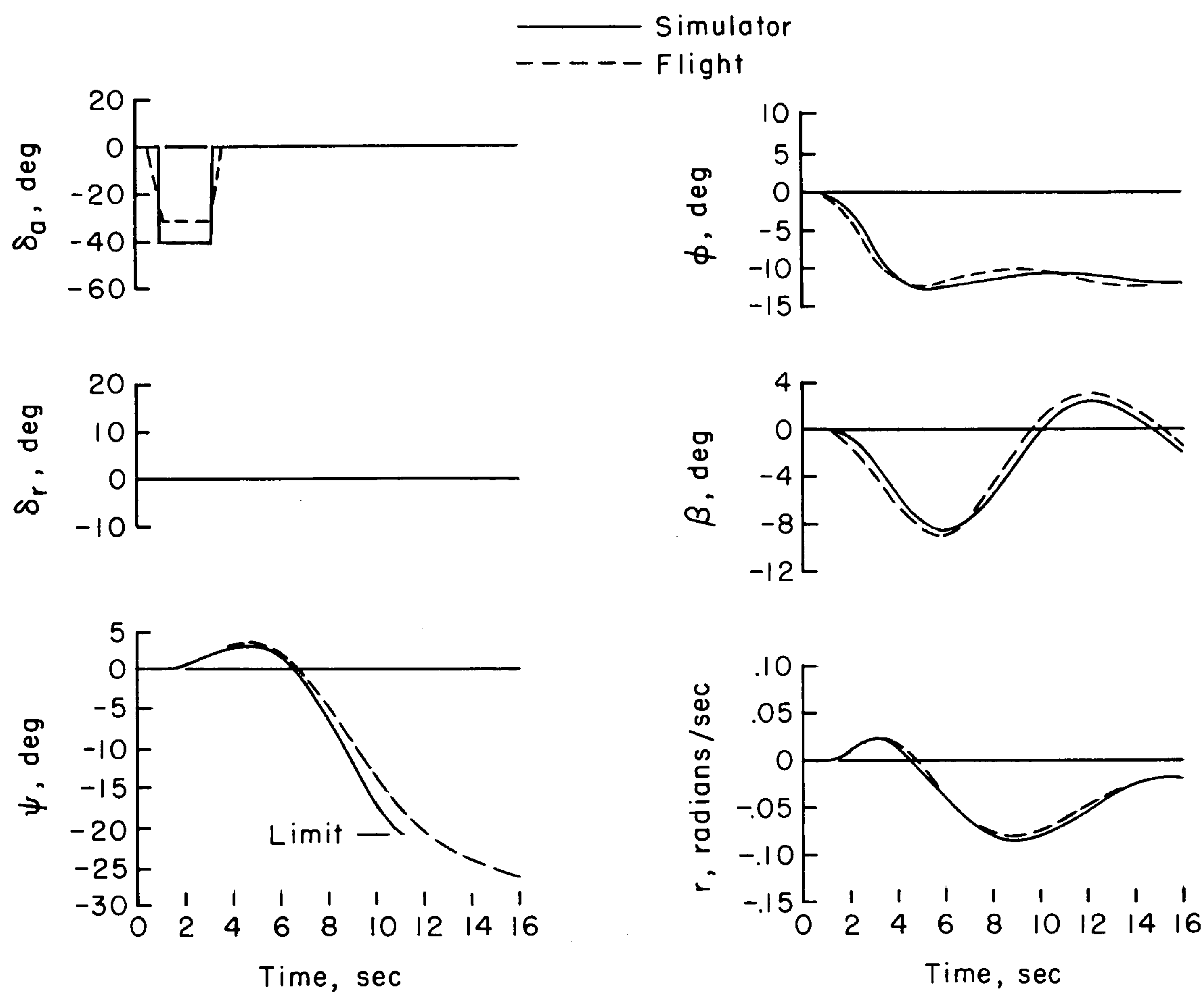

Figure 4.- Comparison of the response of the airplane to a pulse aileron input as obtained from the simulator and from flight (ref. 3).

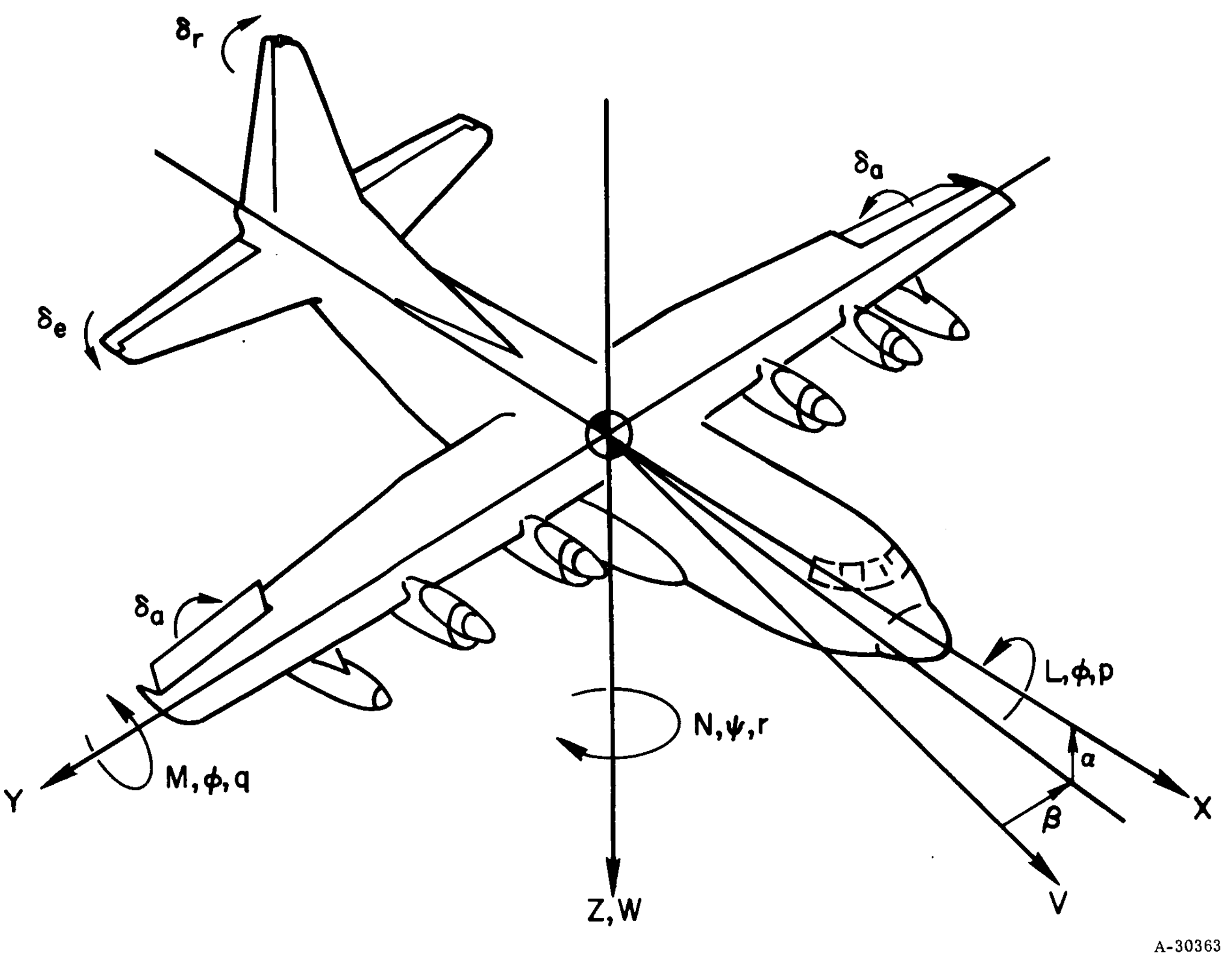

Figure 5.- Positive directions of the forces, moments, air-flow angles, and control deflections.

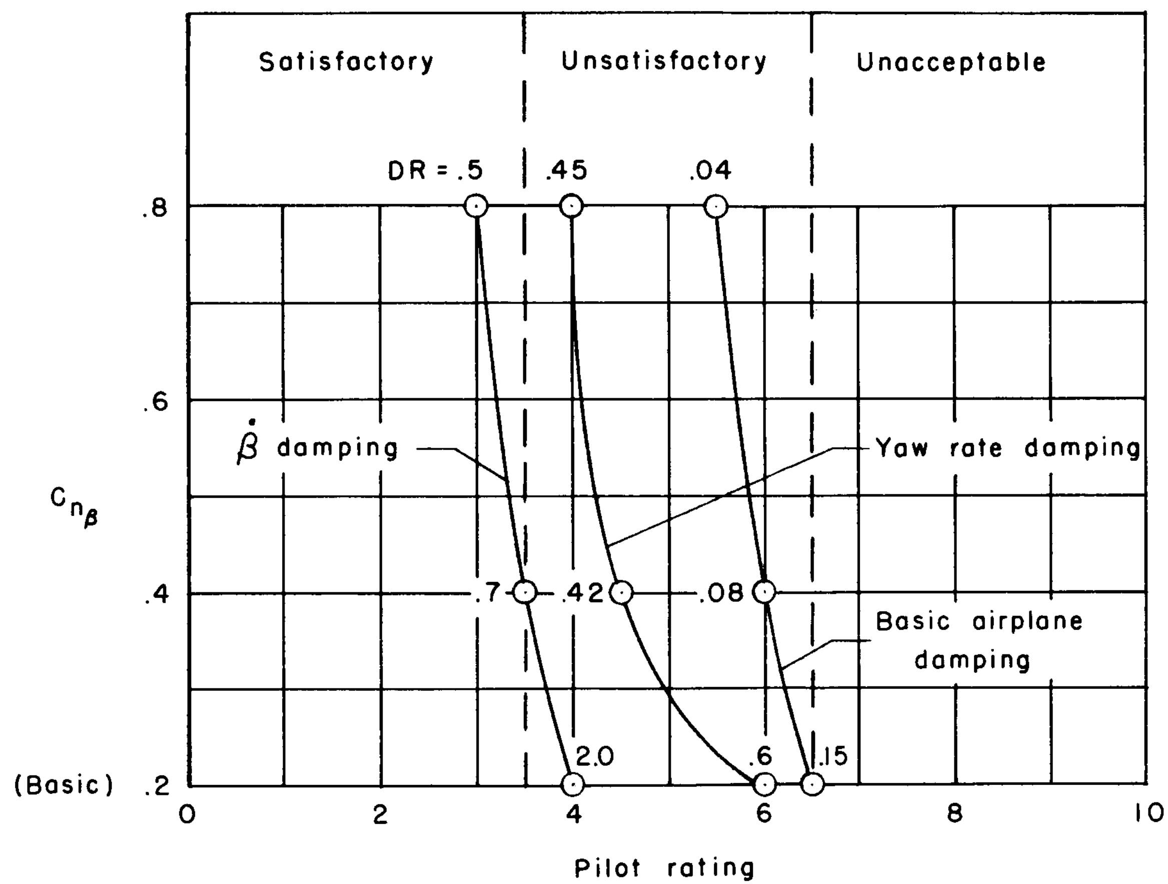

Figure 6.- Variation of pilot rating with yawing moment due to sideslip for various types of damping.

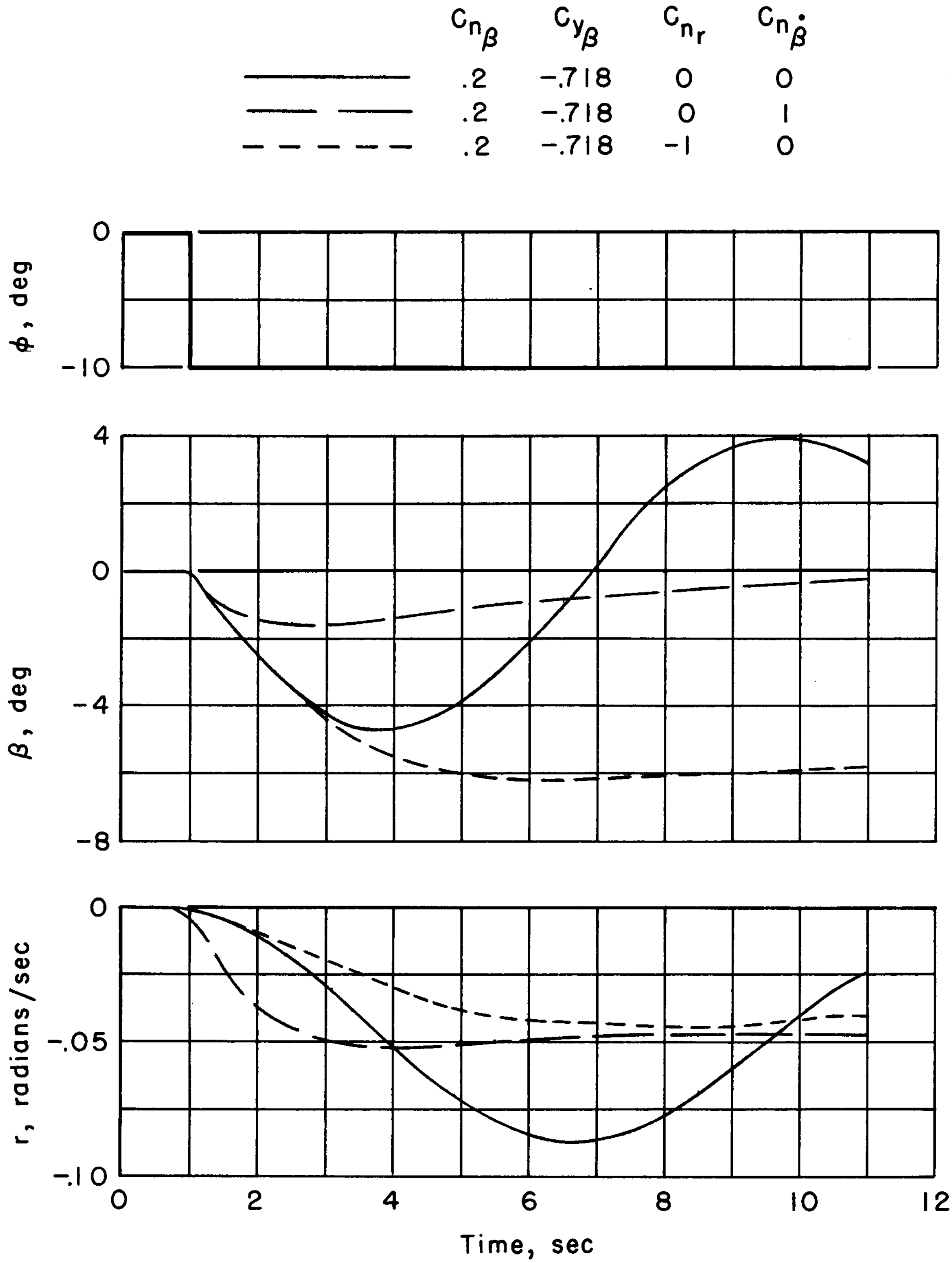

Figure 7.- Time history of sideslip and yaw rate following step bank angle input as computed from simplified equation of motion.

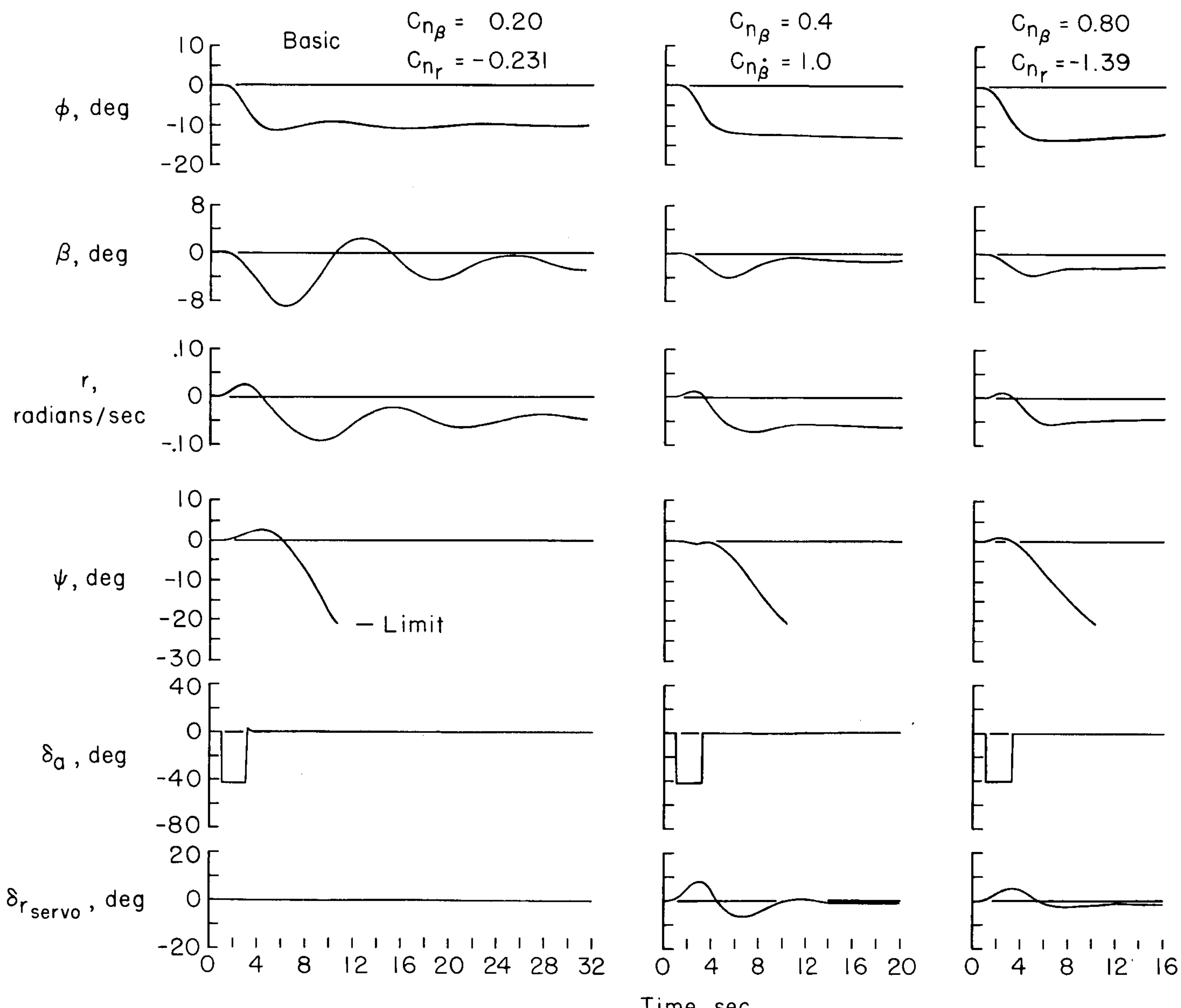

Figure 8.- Time histories of response to pulse aileron input for three configurations.

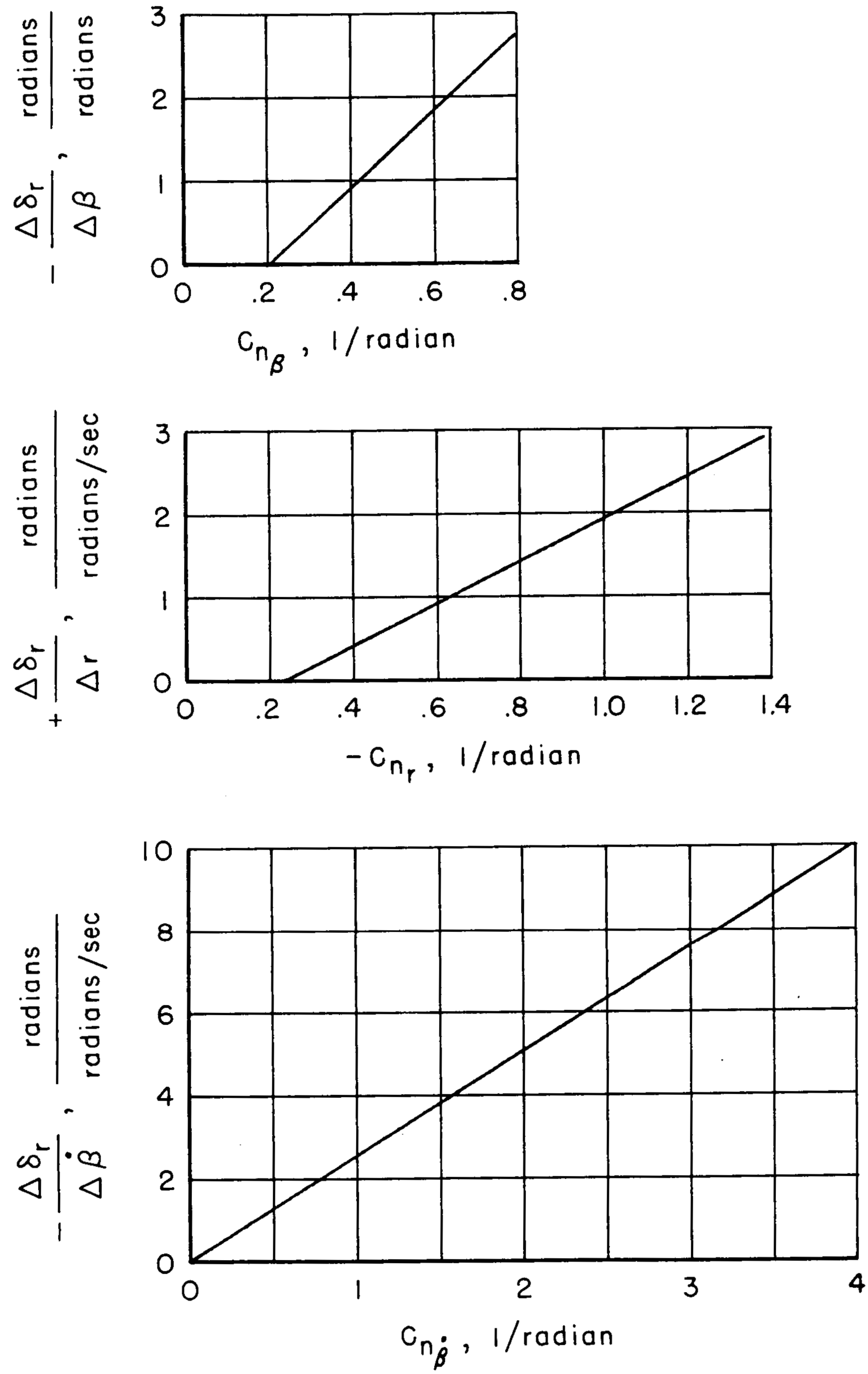

Figure 9.- Stability augmentation gains.